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UCRL-TR-222274

Some Physics Processes in the Nitrogen-Filled Photoluminescence Cell

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June 20, 2006

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

LCLS XTOD Technical Note

Some physics processes in the nitrogen-filled photoluminescence cell

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1. Introduction

The photoluminescence cell is a viable candidate for monitoring the total energy in the Linac Coherent Light Source [1]. In Ref. [1], most of the discussion was concentrated on the cell with argon as a working gas. In the present note I provide a discussion of some physics processes that may affect the performance of the photoluminescence cell with the nitrogen fill. In particular, I will consider the role of the space charge effects, ambipolar diffusion, and recombination processes. This group of phenomena determines the duration of the afterglow process that follows an initial short (<100 ns) burst of optical radiation. The presence of this afterglow can be of some significance for the detection system.

The general template for this discussion follows a draft report where the argon-filled cell was considered. But some processes in nitrogen are different and require separate consideration. In what follows, I am not attempting to produce "exact" results, but rather to provide a quick order-of-magnitude scoping study.

2. Space charge effects

To get some orientation in the role of space-charge effects, we consider an electric potential created by a bare ion cylinder of a radius r situated inside a conducting grounded cylinder of a radius R. This very crude model allows us to get some insight into the possible significance of space-charge effects: if the resulting potential well (for the electrons) is much deeper than their characteristic energy, this would mean that the electrons will be bound to the ion core, and we will actually deal with a quasineutral plasma. The potential at the axis of a cylinder of a radius r is

$$\varphi = q(1 + 2\ln\frac{R}{r}), \tag{1}$$

where q is the charge per unit length.

The number of ions produced by the X-ray beam per unit length:

$$N_i \approx An_0\sigma_{ph}N_X \tag{2}$$

where n_0 is the neutral gas particle density, σ_{ph} is the photoionization cross-section for the incident X-ray beam, N_X is the number of x-ray photons in one pulse, and A (=50 – 200)

is the number of ions produced by one primary electron. So, the potential well for the electrons will be roughly

$$U = e\varphi \approx Ae^2 n_0 \sigma_{ph} N_x (1 + 2\ln\frac{R}{r}) \quad (3)$$

The coefficient $n_0\sigma_{ph}$ is approximately equal to ε/L, where ε is a fraction of the energy lost by the X-ray beam in the cell, and L is the length of the cell. The number of X-ray quanta is

$$N_X \approx 6.4 \times 10^{12} \frac{Q(mJ)}{E(keV)} \quad (4)$$

In other words, we get the following expression for the electrostatic confinement potential (in "practical" units):

$$U(eV) \approx 0.9 \times 10^6 \frac{A\varepsilon Q(mJ)}{L(cm)E_X(keV)} (1 + 2\ln\frac{R}{r}) \quad (5)$$

The dependence on the outer shell radius is weak. We will replace the quantity in the bracket just by 1. Another rough approximation that we make is that

$$\frac{A}{E_X(keV)} \sim 50 \quad (6)$$

When making this estimate, we imply that the primary photoelectron loses its energy before it hits the walls (see S. Hau-Riege memo of May 30, 2006), i.e., the cell size is large enough.

A "practical" equation for the number of ions N_i (including the secondary ions) produced per unit length, reads as:

$$N_i(cm^{-1}) = 3.2 \times 10^{14} \frac{\varepsilon Q(mJ)}{L(cm)} \quad (7)$$

The assumptions are the same as before.

Taking Q=2 mJ, ε=0.01, and L=25 cm, we find from Eqs. (5) and (6) that U=3.7·10^4 eV. In other words, space charge effects for the secondary electrons could be very significant and would prevent them from leaving the ionized core. The temperature of the secondary electrons will be a few electron-volts (it must be well below the excitation threshold).

This is, however, not the case for the primary photoelectrons: for them, the factor A is missing, and U becomes at best comparable to their initial energy (but, more typically, lower than that). So, the primary electrons will perform ionization in a large volume, with the size of order of their range.

Perhaps, the introduction of a very weak magnetic field (~ 150 G for the X-ray energies up to 2. 5 keV) could make the performance of the cell more predictable, by localizing the energy deposition by the primary electrons (the gyro-radius of 2.5 keV electrons in a 150 G field is roughly 1.2 cm).

After the final state of ionization is reached, the space charge effects become important (even for ε as small as 0.0001). In other words, in the final state we get a weakly ionized plasma with the electron temperature of a few electron-volts.

This state is reached within the time of order of 10 or so nanoseconds (depending on the gas density). The lifetime of typical excited states is of order of a few tens of nanoseconds. So, the first burst of optical radiation comes out within the time shorter than 100 ns.

3. Initial state of the plasma

As the range of the primary photoelectrons is typically comparable with the cell radius, we assume that the initial plasma is uniformly distributed over the cell. For a spherical cell of a radius *R*, the ion density will be then

$$n_i = \frac{3N_i}{2\pi R^2}, \tag{8}$$

or, using Eq. (7),

$$n_i(cm^{-3}) = 0.75 \times 10^{14} \frac{\varepsilon Q(mJ)}{[R(cm)]^3}. \tag{9}$$

Obviously, there is some inconsistency in using a cylindrical geometry in the electrostatic analysis and a spherical one in this section, but this inconsistency does not lead to an error greater than a factor of 2 or so. The density evaluated from Eq. (9) is orders of magnitude smaller than the typical neutral gas density. So, the plasma at the end of the ionization pulse is weakly ionized, with the electron temperature of order of 2-3 eV.

4. Energy equilibration with the neutral gas

The collisions with the gas molecules will gradually cool the electrons down. This takes time of roughly

$$\tau_{cooling} = \frac{M}{m} \frac{1}{n_0 \sigma_{e0} v_{Te}}, \tag{10}$$

where *m* and *M* are the electron and the molecule mass, respectively, and σ_{e0} is the electron-molecule cross-section. Taking as a representative value for the latter 10^{-15} cm^2, we find that

$$\tau_{cool}(s) \sim \frac{2.4 \times 10^{-5}}{p(torr)\sqrt{T(eV)}}. \tag{11}$$

Taking *T*~1/40 eV and p~1 torr, one finds that the temperature equilibrium will be reached within ~ 0.1 ms.

The ion component of this plasma will consist of molecular ions, N_2^+, and atomic ions N^+. I haven't looked up the branching ratio yet. The composition may be important in the evaluation of the dissociative recombination. The ion temperature stays close to the gas temperature during all the times of interest for us.

5. Volumetric recombination

If the ions are mostly the molecular ions, then the 2-body recombination process will be dominated by the dissociative recombination. I haven't found information about its rate for nitrogen. If one assumes that the rate is a few times less than for oxygen, i.e., the rate constant is 10^{-6} cm^3/s, then the recombination time will be

$$\tau_2(s) = \frac{10^6}{n_i(cm^{-3})}. \tag{12}$$

The 3-body recombination recombination time at room temperature, (1/40) eV, is:

$$\tau_3(s) = \frac{7 \times 10^{18}}{[n_i(cm^{-3})]^2}. \tag{13}$$

For the typical ion density of 10^9 cm^{-3} (see Eq. (9)), this time is 7 s, i.e., orders of magnitude longer then the distance between the pulses.

We see that a lot will depend on the branching ratio between formation of the molecular and atomic ions. If the latter ion species is dominant, then the recombination time will be very long.

6. Ambipolar diffusion

If the volumetric recombination is indeed very slow, the ionized state will decay by the diffusion of the ions to the walls and the surface recombination. This diffusion will occur at a rate determined by the ion mean-free path λ_i determined by elastic scattering on the neutrals and charge exchange process. As a representative value of this mean free path we take the following estimate:

$$\lambda_i(cm) \sim \frac{10^{-2}}{p(torr)} \tag{14}$$

The diffusion coefficient at a room temperature will then be (for nitrogen)

$$D(cm^2/s) \sim \frac{200}{p(torr)} \tag{15}$$

For a sphere of a radius R, the diffusion time to the walls can be evaluated as

$$t_{diff} \sim \frac{R^2}{6D} \tag{16}$$

or, in "practical" units,

$$t_{diff}(s) \sim 10^{-3}[R(cm)]^2 p(torr) \qquad (17)$$

For the expected range of pressures in the gas cell, the diffusion time is typically longer than the distance between the successive pulses at 120 Hz rep rate. This means that there will be a continuous presence of the ionized component in the cell (unless the recombination is fast enough). The time of the gas replacement in the cell due to the continuous outflow through the 3-mm diameter end apertures for the assumed radius of the cell $R\sim$ 10 cm is of the order of 1 s, much longer than 1/120 s separation between the pulses.

Summary

The first short burst of the optical radiation will be followed by a much longer afterglow. The duration of the latter, in the case of the nitrogen gas, will be strongly depended on the relative concentration of molecular and atomic ions of nitrogen. The branching information should be available in the literature. A literature search will be needed.

Some effect on the conclusions of this paper may have the formation of the negative molecular ions N_2^-. The negative atomic ions N^- do not exist. I did not have enough time to find out whether the molecular ions exist.

A universal cure for reducing the afterglow time (be it needed) is introduction of a weak guiding magnetic field of ~ 150 G. This field will lead to a reduction of the radius of the ionized zone, increase of the ion density, and corresponding increase in the recombination rate.

This work was performed under the auspices of the U.S. Departent of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

References.

[1] D. Ryutov, R. Bionta, and S. Hau-Riege. “Photoluminescence for non-destructive total energy measurements and imaging of X-ray beam in the Linac Coherent Light Source,” UCRL-TR-220017-DRAFT, March 2006.